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Safety and Environmental Impact Reduction. A Case-Study Applied to Coal Dry Distillation Industry

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1. Introduction

As reported by Trevor Kletz, changes made to improve the environment have sometimes produced unforeseen and hazardous side-effects. Before changing designs, or methods of operation we should try to foresee their effects and we should balance the risks to people against the risks to environment. Notwithstanding technological development, enforcement of ATEX Directives and safety management system application, explosions in the process sector still claim lives and severe economic losses. Experience shows that in the process industry high severity events frequently occur in auxiliary areas, such as transport and storage of raw materials and products (Fabiano and Currò, 2012). Even a consolidated process like coke dry distillation allows the opportunity of preventing environmental impact, reducing as well explosion risk connected to fugitive emissions. In this activity, two intervention lines were identified: the former deals with accident risk, i.e. the occurrence of hazardous factors that may cause the ignition of coke oven gas during work activities on pressurized gas pipelines. The latter concerns environmental risk reduction referred to the transport of raw material from the harbour temporary storage site to the final plant. Considering explosion risk in confined environment and possible evolving scenarios, a short-cut mathematical approach to the maximum allowed hazardous substance build-up is developed based on the intrinsic hazards of the released material. This framework from one side will help identifying and assessing small hazardous releases consequences in closed areas and set-up appropriate control measures. From the other side, it is adopted in connection with the design of an underground conveyor belt for coal, so as to limit fugitive emissions. In this context, the study involves an in-depth quantitative risk assessment and the planning of severe control and prevention measures suitable to mitigate explosion/fire risk, both reducing the probability and the severity of adverse consequences. The methodology successfully tested at the real-scale can be applied to more complex situations, allowing, as well, the attainment of a more generalized approach for the design, once given the release parameters, the building and plant layout.

2. Theoretical considerations

2.1 Allowed build-up

The problem of concentration build-up in closed environment is of practical interest in many industrial processes, as well as in natural or forced ventilation design for health and safety purposes. Risk assessment required by ATEX Directive requires the application of proper quantitative methodologies (Lisi et al., 2008). Therefore, there is a need in the assessment of the maximum admissible build-up, in connection with adverse effects, so as to foresee the effectiveness of techniques in reducing the possible consequences of the unwanted events. A simple unified approach is proposed for the conservative evaluation of the maximum admissible concentration of gas or dust. The allowed build-up is here defined as the maximum amount of the flammable compound in the environment following the continuous release, evaluated on the basis of tolerable effects on human in case of ignition. On this basis, the allowed build-up

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can be identified making reference to the corresponding hazards for man inside the building, namely overpressure and radiating heat exposure. Clearly, in case of compounds characterized by different intrinsic hazards, the safety evaluation must consider as well the corresponding hazardous scenarios, e.g., toxicity (CO) or thermal instability (C_2H_2). In order to approach the allowed build-up evaluation reference is made to following scenario: instantaneous combustion of the whole mass of flammable substance and complete mixing of combustion products with air inside the enclosure. We assume that the maximum admissible overpressure corresponds to the threshold value for man injury, assuming an average conservative value quoted from different sources, i.e. ($\Delta p^* = 0.07 Pa$). The safety criterion, in terms of overpressure, can easily be expressed as $\Delta p \leq \Delta p^*$ and the final pressure can be roughly calculated by Eq. (1):

$$p_e = p_0 \frac{n_e}{n_0} \frac{T_e}{T_0} \tag{1}$$

The values of n_e and T_e are calculated taking into account the most conservative situation, i.e., those corresponding to the maximum overpressure value. Assuming by definition that n_a (mol) be the flammable release build-up inside the building up to the ignition time, the maximum temperature value, corresponding to the whole absorption of the reaction heat by the air-smoke mixture, can be easily calculated by:

$$T_e = T_0 + \frac{n_a(-\Delta \tilde{H}_c)}{n_e \tilde{c}_{pe}} \tag{2}$$

The value of n_e depends upon the degree of confinement of the building where the release takes place and on the combustion stoichiometry, as follows:

$$n_e = n_0 + \alpha n_a + n_a \sum \frac{\nu_i}{\nu_a} \tag{3}$$

In Eq. (3), the term αn_a accounts for the gas quantity connected to the combined effects of the release and the exchange with the external environment due to aeration and the last sum must consider only gaseous components. Generally speaking, it results: $0 \leq \alpha \leq 1$, with following limiting cases:

- completely sealed enclosure: $n_a = n_r$; $\alpha = 1$;
- well ventilated building, small quantity released: $\alpha \cong 0$;
- condensed phase release: $\alpha \cong 0$.

In connection with the most critical situation, i.e. totally confined environment, Eq.(3) can be rearranged as:

$$n_e = n_0 + k n_a \tag{4}$$

By combining Eqs. (1)-(4), one can write:

$$\Delta p = \frac{p_0}{n_0}\left(k + \frac{(-\Delta \tilde{H}_c)}{\tilde{c}_{pe} T_0}\right) n_a \cong \frac{p_0}{n_0 T_0} \frac{-\Delta \tilde{H}_c}{\tilde{c}_{pe}} n_a = \frac{R}{V} \frac{-\Delta \tilde{H}_c}{\tilde{c}_{pe}} n_a \tag{5}$$

The approximation in Eq. (5) is justified, being the term k lower by two order of magnitude with respect to the other term under parenthesis in the same Eq. (5), when dealing with standard plant applications.

$$n_a^* = \frac{\Delta p^* \tilde{c}_{pe}}{-\Delta \tilde{H}_c R} V \tag{6}$$

$$n_a^* \cong \frac{25}{-\Delta \tilde{H}_c} V \tag{7}$$

or else, defining $y_a = \frac{n_a}{n_0}$,

$$y_a^* \cong \frac{\Delta p^*}{p_0} \frac{\tilde{c}_{pe} T_0}{-\Delta \tilde{H}_c} \tag{8}$$

that under standard environmental conditions (SATP) yields:

$$y_a^* \cong \frac{600}{-\Delta\tilde{H}_c} \tag{9}$$

It can be observed that $y_a^* <<< 1$, so that, practically speaking, the maximum allowed build-up can be expressed in terms of mean molar fraction of flammable gas accumulated within the enclosure:

$$y_a^* = \frac{n_a^*}{n_0} \cong \frac{n_a^*}{n_0 + n_a^*} \tag{10}$$

This value can be compared with the low flammable limit (LFL) of the released compound in air showing a value lower by at least one order of magnitude. It follows that the condition $y_a < y_a^*$ guarantees the impossibility of fire propagation inside the building, even in presence of an effective ignition source. However, it must be noticed that the presence of limited internal regions where $y_a > y_L$ cannot be excluded "a priori", for example referring to the neighbourhood of the release point. The volumes connected to a possible fire would result intrinsically limited, especially under well mixing conditions (released gas density comparable with air density and adequate ventilation). Under these circumstances, even in presence of an ignition source, the consequences would be negligible, due to the low mass fraction of fuel involved. On the contrary, a different approach must be considered in case of formation of gas pockets with density significantly different from the air one, in connection with low aeration condition and/or particular geometrical configuration of the room where the release occurs. In this case, even if the safety constrain previously expressed and the derived limitation according to Eqs. (6) and (8) be respected, a fire development in the flammable regions would give rise to possible relevant thermal radiation damage for a man operating in the proximity of the flame. The theoretical analysis was extended and applied to confined release from coke ovens (Figure 1) to define safety conditions representing the limiting and most conservative constraints. The same approximated approach can be adopted also dealing with coal dust (considered as C for the stoichiometry balance). By multiplying both terms of Eq. (7) by M/V, we can easily obtain the following conservative final expression.

$$\rho_a^* \cong \frac{300}{-\Delta\tilde{H}_c} \tag{11}$$

The constraints expressed by Eqs. (9) and (11) may lead to overly conservative preventive and protection measures, since the calculated average values are by far lower that the lower explosion concentration.

2.2 Underground coal transport

The technical problem of limiting fugitive coal emissions during the transportation phase by wagons from the harbour, is faced by the design of an underground mini-tunnel with an open pipe conveyor, properly equipped and instrumented. It stands to reason that this technique allows facing decisively air pollution caused by fugitive dusts by applying an inherent safety prevention criterion, but requires the development of a proper risk assessment. To this end, reference is made to the physical model of an underground conveyor system with sloping angle θ and to a control volume characterized by a length *dx* and a transversal area dA_x, as schematized in Figure 2.

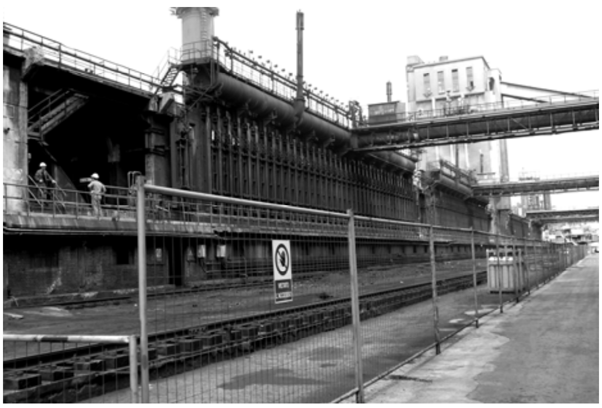

Figure 1: Coke oven batteries of a dry distillation plant.

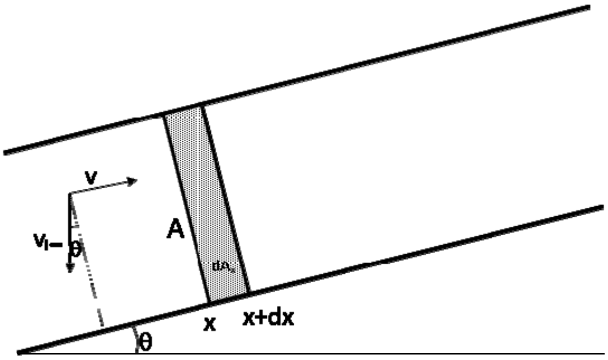

Figure 2: Simplified physical model of the underground conveyor system.

Figure 3: Underground conveyor belt inside a concrete-made mini tunnel, with safety equipments.

We assume that dust concentration is constant in each tunnel section normal to the ventilation flux. This conservative hypothesis determines an underestimation of the dust deposition and consequently an overestimation of dust concentration in air. In fact, for a given average concentration on a section, dust particles are more concentrated in the first layers near the coal surface, with consequent higher sedimentation velocity.

The net dust flux of the *i*-th granulometric class leaving the volume due to the combined velocity is:

$$d\dot{m}_i = d(\rho_i v_n A) = (v - v_{i\infty} sin\theta) bh \cdot d\rho_i \tag{12}$$

the net dust flux of the *i*-th granulometric class leaving by sedimentation the is:

$$d\dot{m}_d = \rho_i v_{nA_x} dA_x = \rho_i v_{i\infty} \cos\theta \cdot b \cdot dx \tag{13}$$

the net dust flux of the i-th granulometric class entering the volume by suspension mechanism is:

$$d\dot{m}_s = \dot{m}''_{si} dA_x = \dot{m}''_{si} \cdot b_c \cdot dx \tag{14}$$

Under steady-state conditions, the mass balance can be expressed by:

$$(v - v_{i\infty} sin\theta) bh \cdot d\rho_i = \dot{m}''_{si} \cdot b_c \cdot dx - \rho_i v_{i\infty} \cos\theta \cdot b \cdot dx \tag{15}$$

from which we can write:

$$\frac{d\rho_i}{dx} = \frac{\dot{m}''_{si} \dfrac{b_c}{b} - \rho_i v_{i\infty} \cos\theta}{(v - v_{i\infty} sin\theta) h} \tag{16}$$

By integration, under the boundary condition $\rho_i(0) = \rho_{i0}$, one can write:

$$\frac{1}{v_{i\infty} \cos\theta} ln \frac{\dot{m}''_{si} \dfrac{b_c}{b} - \rho_{i0} v_{i\infty} \cos\theta}{\dot{m}''_{si} \dfrac{b_c}{b} - \rho_i v_{i\infty} \cos\theta} = \frac{x}{h(v - v_{i\infty} sin\theta)} \tag{17}$$

from which it can be easily obtained the final expression:

$$\rho_i = \rho_{i0} + \left(\frac{b_c}{b} \frac{\dot{m}''_{si}}{v_{i\infty} \cos\theta} - \rho_{i0} \right) \left(1 - e^{- \frac{v_{i\infty} \cos\theta}{(v - v_{i\infty} sin\theta)} \frac{x}{h}} \right) \tag{18}$$

3. Results and discussion

Applying the developed approach to the under coke oven enclosures, where low flow rate releases of gas mixture (mainly hydrogen, methane and light HC) can occur, it is possible to size venting areas and needed ventilation rates. As detailed elsewhere (Palazzi et al., 2011), analysis showed the need to install as well gas sensors (CO/H_2) and ensure a reliable periodic inspection program, according to a frequency preventing the attainment of critical build-up. A picture of the underground conveyor belt localized inside a concrete-made mini tunnel (1,100 m long; 7 m^2 cross section) is shown in Figure 3. The plant will be provided by an active system for the containment of the coal dust, powered by suitable film-forming foam containing dust emission for at least 20 min. An automatic system provides the dosage of film-forming water foam by injection in seven feeding points. Each dosing station will be equipped with suitable control systems and signalling of the level of water foam in the tank. Three dosage points are distributed on the belt and four points are located along the whole height of an intermediate silos. These last four points act as follows: the injectors positioned at the upper and lower ends will act continuously while the sprayers located at one third and two thirds of the total fall height will be controlled by opacity meters and will intervene only in case of increased dust concentration, so as to avoid hazardous dust conditions. The whole control and emergency system is fully automatic, requiring human intervention only during maintenance operation. The ventilation system is designed to ensure the necessary and adequate ventilation rate maintaining the mini tunnel in constant depression with respect to the outside environment. It will be equipped with suitable aeration towers, installed close to the ends of the tunnel and of the intermediate well. Considering environmental risk reduction and underground coal transport design, the results obtained by the application of the model are presented in graphical form in Figures 4 and 5. Reference is made to granulometric distribution experimentally obtained in the proximity of coal open piles, under low wind velocity conditions. Based on these findings we assume a bi-modal distribution corresponding to the two most frequent particle diameters, i.e. dp_1 = 5 μm; dp_2 = 20 μm. Figure 4 shows the dust concentration profiles along the transportation plant, with belt velocity v = 2.5 $m \cdot s^{-1}$, for the two granulometric classes (respectively ρ_1 and ρ_2) and the total dust concentration (ρ_T). Reference is made to steady-state conditions and average air velocity of 0.5 $m \cdot s^{-1}$, in connection with a cautious value of dust emissivity, resulting from different authors and experimental tests, equal to $\dot{m}''_{s,base} = 0.01 gm^{-2}s^{-1}$. In case of ventilation absence, the dust concentration profiles are depicted in Figure 5. From both figures one can notice the combined influence of the suspension mechanism, which dominates for low diameter particles and the deposition effect. As a concluding remark, we can observe that the maximum concentration attainable under all considered conditions is at least one order of magnitude lower than the minimum explosive dust concentration (MEC=30 $g \cdot m^{-3}$), notwithstanding all conservative hypotheses made. The concentration is also below the conservative safety criterion for local explosion previously outlined. Even if dust on horizontal surface will not explosively ignite even if accumulated to a depth of one inch (Eckoff, 2003), they can be locally airborne by human interaction, or pose a health hazard. In consideration of the possible staged nature of dust explosion, that can be triggered by a small deviation and local fire, the mini-tunnel was conservatively classified as zone 21, according to the requirement of Directive 94/9/EC, as reported by Fritze (2010). Mitigative safeguards include fire/overheating detection by linear sensors along the conveyor belt and warning systems. In case on fire detection during steady state transport conditions, an automatic fire extinguisher system, including sprinkler systems and fire water monitors is available. In addition, water curtain properly designed (Palazzi et al., 2007, 2009), can be activated so as to limit and segregate the fire zone, allowing as well a safe way for possible human intervention.

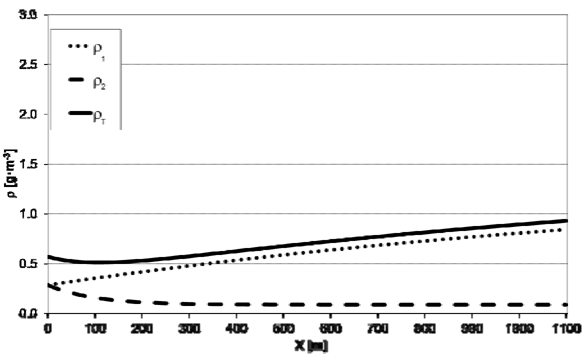

Figure 4: Dust concentration profile along the transportation plant in presence of ventilation.

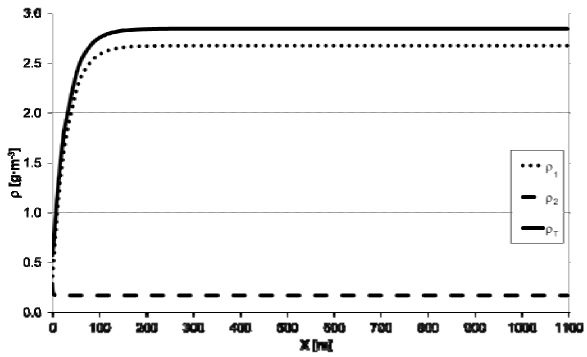

Figure 5: Dust concentration profile along the transportation plant in absence of ventilation.

4. Conclusion

The problem of fugitive emissions and consequent environmental and accident risk can be faced also in consolidated processes and plants, by applying proper technical and managerial solutions. A unified approach was applied to both gas and dust releases, allowing to derive conservative safety constraints. Following safety considerations are summarized, in view of full scale application. Transport equipment must be designed and maintained so as to limit fugitive emissions into the external environment, implementing at the same time all possible measures to prevent explosion hazards. Clearly, the dust characteristics and their possible escape mitigation must be fully understood also on an experimental basis. In addition, enforcing a fully accounted maintenance plan must ensure removal of any coal dust before it accumulates up to hazardous levels. By proper calculations, starting from the model outlined in paragraph 2.2, it is possible evaluating the dust deposition under the different operative situations, so as to quantify the frequency of proper housekeeping activities for the avoidance of hazardous dust accumulation. A robust preventive maintenance program must be enforced, with clear responsibility and accountability, preventing abnormal hazardous deviations, e.g., misaligned rotating equipments creating friction heating, or even sparks.

Nomenclature

A = tunnel cross section, m^2
b = width of the sedimentation area, m
b_c = belt width, *m*
$\tilde{c}_{pe}$ = mean molar heat of the explosive mixture, in the interval T_0-T_e, = 29.1 kJ $kmol^{-1}$ K^{-1}
dp_i = mean diameter of the dust, µm
$\Delta\tilde{H}_c$ = standard hydrocarbon enthalpy of combustion at 298, kJ $kmol^{-1}$
h = tunnel height, m
k = parameter defined as $k = 1 + \sum \nu_i \nu_a^{-1}$
$\dot{m}_d$ = flux of the i-th granulometric class by sedimentation, $g{\cdot}s^{-1}$
$\dot{m}_i$ = flux of the i-th granulometric class due to conveyor velocity, $g{\cdot}s^{-1}$
$\dot{m}_s$ = flux of the i-th granulometric class by suspension mechanism, $g{\cdot}s^{-1}$
$\dot{m}''_{si}$ = specific emissivity, $g{\cdot}m^{-2}{\cdot}s^{-1}$
M = molar mass (referred to C) = 12 kg $kmol^{-1}$
n_a = moles of flammable compound, mol
n_0 = number of moles of air inside the enclosure before the release, mol
p_e = pressure after the explosive combustion, Pa
p_0 = internal pressure before the release, Pa
R = universal gas constant, J $K^{-1}mol^{-1}$
T_e = temperature after the combustion, K
T_0 = ambient temperature before the release, K
v = wind velocity, $m{\cdot}s^{-1}$
v_r = relative velocity, $m{\cdot}s^{-1}$
$v_{i\infty}$ = sedimentation velocity of the i-th granulometric dust class, $m{\cdot}s^{-1}$
V = enclosure volume, m^3
y = mole fraction, -
ρ_a^* = release density at limiting value, kg m^{-3}
θ = sloping angle, rad
ρ_i = density of the i-th granulometric class, $kg{\cdot}m^{-3}$
v_n = net linear velocity of dust, $m{\cdot}s^{-1}$

References

Eckoff R., 2003, Dust explosion in the process industries, 3rd ed., Gulf Prof. Publ., Burlington, USA.

Fabiano B., Currò F., 2012, From a survey on accidents in the downstream oil industry to the development of a detailed near-miss reporting system, Process Safety and Environmental Protection 90, 357-367.

Fritze J.P., 2010, Explosion protection concepts for storage, transport and grinding of coal, In: 13th Loss Prevention, vol. 2, Eds. G. Suter, E. De Radaemaker, 455-458, TI vzw, Brugge, Belgium.

Lisi R., Milazzo M.F., Maschio G., 2008. A quantitative methodology for risk assessment of explosive atmospheres according to the ATEX directive. In: Safety, Reliability and Risk Analysis: Theory, Methods and Applications, vol. 2, 1019-1025, CRC Press, Valencia, Spain.

Palazzi E., Currò F., Pastorino R., Fabiano B., 2011, Evaluation and mitigation of risk connected o lighter than air gaseous releases in confined environment, Chemical Engineering Transactions 24, 1333-1338, DOI: 103303/CET1124223

Palazzi E., Currò F., Fabiano B., 2007, Mathematical modelling of fluid spray curtains to mitigate accidental releases, Chemical Engineering Communications 194, 446-463.

Palazzi E., Currò F., Fabiano B., 2009, From laboratory simulation to scale-up and design of spray barriers mitigating toxic gaseous releases, Process Safety and Environmental Protection 87, 26-34.